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Multi-model assessment of the role of anthropogenic aerosols in summertime climate change in Europe

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Key Points:

- (1) The role of anthropogenic aerosols in European summertime climate change is assessed using a set of multi-model regional climate simulations
- (2) Reduced concentrations of anthropogenic aerosols in Europe lead to an increase in surface solar radiation and an extra warming near surface
- (3) Current differences in aerosol representation explain a part of inconsistencies between global and regional climate projections in Europe

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Abstract

Global and regional climate models (respectively GCMs and RCMs) are delivering conflicting messages about summertime climate change in Europe, revealing notably a weaker warming in RCMs. A dedicated multimodel ensemble of nine GCM-RCM pairs is analyzed to assess the role of anthropogenic aerosols in these inconsistencies. The expected decrease of anthropogenic aerosol concentrations is found both to modify the future evolution of shortwave radiation and to generate an extra warming. For every tenth in aerosol optical depth drop in Central Europe, shortwave radiation is increased at the surface by 6.3 Wm^{-2} and decreased at the top of the atmosphere by 5.6 Wm^{-2} , while near-surface temperature is increased by 0.3°C . The consideration of time-varying anthropogenic aerosols in RCMs thus contributes to improving GCM/RCM consistency in Europe for these three variables, but not for water cycle. The results obtained underline the necessity to better consider aerosols in upcoming regional climate simulations.

Plain Language Summary

As far as summertime climate change in Europe is concerned, global and regional climate models do not provide exactly the same information, insofar as the warming simulated by regional models is notably lower than in global models. The decrease of anthropogenic aerosol concentrations, not always taken into account in regional models, could be one possible explanation of these inconsistencies. This hypothesis is analyzed here with the help of a dedicated multimodel ensemble of simulations with constant and evolving aerosols. This evolution of aerosols is shown to increase surface solar radiation and near-surface temperature in Europe. The consideration of time-varying anthropogenic aerosols in regional climate models thus contributes to reducing the differences between global and regional climate simulations.

1 Introduction

Reliable and robust regional climate change information is becoming central for taking the right decisions in adapting the human society to a rapidly changing climate. Nowadays, this information is mostly based on Global and Regional Climate Models (respectively GCMs and RCMs) regardless of the processing subsequently applied (bias correction, statistical downscaling). GCMs and RCMs are usually considered as complementary and consistent, the former being the forcing of the latter. GCMs are supposed to provide the large scale information whereas RCMs produce more detailed dynamically downscaled climate information for a given large scale (Laprise et al., 2008).

However, several studies (described below) have recently underlined strong inconsistencies at the large scale between the climate change signal derived from GCM-based and RCM-based ensembles, such as the fifth version of the Coupled Model Intercomparison Project (CMIP5, Taylor et al., 2012) and the associated Coordinated Regional Climate Downscaling Experiment (CORDEX, Jones et al., 2011) respectively. While GCM-RCM conflicting messages at regional and local scales (e.g. for European subregions, or mountain areas) can be interpreted as the signature of the RCM added-value in future climate projections (Giorgi et al., 2016; Torma & Giorgi, 2020), they are not expected to occur systematically at the large scale (e.g. at the European scale). Such conflicting messages may create confusion for climate model data users such as impact communities, stakeholders and operational climate services. Not understanding or trying to solve these problems could lead to downgrade the confidence in the capacity of climate models to provide reliable information on climate change at regional level.

So far, most of the detected conflicting messages have been revealed for summertime climate change in Europe for surface solar radiation (Bartók et al., 2017; Boé et al., 2020; Gutiérrez et al., 2020; Coppola et al., 2021; Chen, 2021), cloud cover (Bartók et al., 2017; Cherif et al., 2020), near-surface temperature (Boberg & Christensen, 2012;

74 Sørland et al., 2018; Schwingshackl et al., 2019; Boé et al., 2020; Coppola et al., 2021;
75 Ribes et al., 2022) and precipitation (Sørland et al., 2018; Boé et al., 2020). In this re-
76 gion, RCMs show a weaker warming and a weaker drying than their driving GCM in sum-
77 mer. Value differences can reach up to -30 Wm^{-2} and -4.5°C at the end of the 21st cen-
78 tury under the Representative Concentration Pathway RCP8.5 scenario (Boé et al., 2020),
79 order of magnitude of the climate change signal. For some variables, the inconsistency
80 can even lead to a reversal of the sign of climate change, with GCMs showing for exam-
81 ple a clear increase in the surface solar radiation at the end of the 21st century whereas
82 the RCMs show a decrease or only a small increase (Bartók et al., 2017; Boé et al., 2020;
83 Gutiérrez et al., 2020). The identification of the inconsistencies is robust through var-
84 ious analysing approaches, large multi-model ensembles and clean GCM-RCM pairs (Boé
85 et al., 2020; Coppola et al., 2021; Taranu et al., 2022). Moreover it is verified for var-
86 ious temporal horizons and socio-economic scenarios (Boé et al., 2020; Gutiérrez et al.,
87 2020; Coppola et al., 2021). It is noteworthy that the inconsistency level strongly depends
88 on the choice of the GCM-RCM pair (Bartók et al., 2017; Boé et al., 2020; Gutiérrez et
89 al., 2020; Taranu et al., 2022), which tends to invalidate the conclusion about the pre-
90 dominance of the role of the increased horizontal resolution in explaining these incon-
91 sistencies.

92 Various hypotheses have been proposed to explain these GCM-RCM conflicting mes-
93 sages: different behaviours in the simulated cloud cover (Bartók et al., 2017), missing
94 aerosol forcing in RCMs (Boé et al., 2020; Gutiérrez et al., 2020; Chen, 2021; Schumacher
95 et al., 2024), missing air-sea coupling in RCMs (Boé et al., 2020), smaller present-climate
96 biases in RCMs (Sørland et al., 2018), missing plant physiological CO_2 effect in RCMs
97 (Schwingshackl et al., 2019), and GCM-RCM inconsistencies in physical parameteriza-
98 tions (Taranu et al., 2022). Those competing and often contradictory arguments have
99 so far failed to firmly establish the main factors explaining the GCM-RCM inconsisten-
100 cies in Europe, partly because these studies use either one single model or simulation en-
101 sembles without dedicated sensitivity tests. Similar GCM-RCM inconsistencies have also
102 been reported over other regions such as North America (Chen, 2021).

103 Antagonistic effects between, on one side, greenhouse gases which induce a pos-
104 itive radiative forcing and strongly contribute to global warming and, on the other, an-
105 thropogenic aerosols which induce a negative radiative forcing and whose emissions evo-
106 lution in the 20th century explain the dimming/brightening phenomenon (Wild, 2009),
107 have long been identified (Ramanathan & Feng, 2009). The evolution of greenhouse gases
108 and anthropogenic aerosols is generally included in GCMs, but not systematically for
109 aerosols in most RCMs up to now (Gutiérrez et al., 2020). Anthropogenic aerosols are
110 therefore a good candidate to explain the identified conflicts, given the main role of this
111 specific forcing in past European climate change through the dimming effect since the
112 1980s (Wild, 2009; Philipona et al., 2009; Nabat et al., 2014; Wild et al., 2021; Schumacher
113 et al., 2024), their tendency to decrease in 21st century scenarios over the area (Gutiérrez
114 et al., 2020; Drugé et al., 2021), and more generally the complexity and the large regional
115 variations in aerosol climate effects (Persad et al., 2023).

116 In this study, we intend for the first time to use a dedicated multi-model sensitiv-
117 ity study to pursue the two following complementary objectives: (1) specifically assess
118 the role of anthropogenic aerosols in explaining the GCM-RCM conflicting messages in
119 summertime climate change in Europe and (2) quantify the role of the aerosol change
120 in future climate change projections over Europe. The simulation ensembles used for this
121 purpose covers a large RCM and GCM diversity, consisting in sensitivity runs with and
122 without evolving aerosols in near-future projections. The following analyses focus on cli-
123 mate change signal in the near future (2021-2050), regarding radiation, near-surface (at
124 2m) temperature and water cycle.

125 2 Methodology

126 2.1 The coordinated multi-model experimental protocol

127 This study has been designed in the framework of the CORDEX Flagship Pilot Study
 128 on aerosols (FPS-aerosol, Solmon & Mallet, 2021), and relies on a protocol of coordinated
 129 multi-model simulations addressing both of the above objectives (Protocol 1B, Somot
 130 et al., 2021). This protocol can be seen as a sensitivity experiment to assess current prac-
 131 tices in CORDEX RCMs with regards to considering the evolution of aerosols. Indeed,
 132 the aerosol forcing and its evolution in historical and scenario runs was not specified in
 133 the CORDEX experimental protocol aiming at downscaling CMIP5 GCMs, which may
 134 lead to GCM/RCM inconsistencies, with potential impacts on the simulated climate change
 135 signal.

136 The current protocol relies on existing Med- and EURO-CORDEX baseline sim-
 137 ulations downscaling CMIP5 GCMs, and new RCM sensitivity simulations, as follows:
 138 (1) one simulation covering the historical period 1971-2000, (2) a second simulation cov-
 139 ering the period 2021-2050 for the RCP8.5 run, and (3) an additional future scenario that
 140 is a perfect twin of the CORDEX standard run (2021-2050), but with respectively evol-
 141 ving (constant) aerosols if the aerosols were constant (evolving) in the official CORDEX
 142 simulation. These simulations are respectively named RCMhis, RCMevol and RCMcst
 143 thereafter.

144 2.2 Description of multi-model simulations

145 The ensemble of regional simulations consists in nine GCM-RCM pairs, perform-
 146 ing the three simulations listed above. The GCM-RCM pairs combine six different RCMs
 147 (whose horizontal resolution ranges from 12 to 50 km), driven at their lateral boundaries
 148 by six different CMIP5 GCMs (Table 1).

149 Aerosols are considered through monthly means of aerosol optical depth (AOD)
 150 fields given the absence of full tropospheric chemistry in these simulations. These AOD
 151 fields evolve over time in RCMevol, but remain annually constant in RCMcst. They come
 152 either from the driving GCM if possible, or from an aerosol climatology in which the tem-
 153 poral evolution has been added (Szopa et al., 2013). This temporal evolution of aerosols
 154 was originally included only in the official EURO-CORDEX simulations of ALADIN63
 155 and RACMO22E, while for COSMO-crCLIM, REMO2015 and RegCM, aerosols were
 156 constant. Aerosol-radiation interactions are considered in all simulations (aerosol direct
 157 effect). Regarding aerosol-cloud interactions, only ALADIN63 includes the cloud-albedo
 158 effect (only involved in the radiative code and not in the cloud parameterization), while
 159 none of these RCMs incorporates the other aerosol indirect effects on cloud microphysics.

160 This ensemble of simulations is highly diversified, all at once in terms of GCMs,
 161 RCMs, aerosol datasets, and in the representation of the radiative effects of aerosols. To
 162 our knowledge, this is the first time that such a large and diverse ensemble has been used
 163 to estimate the effects of aerosols on climate at the regional scale, and their impact on
 164 the GCM-RCM inconsistencies.

165 3 Impact of evolving aerosols on regional climate projections

166 Anthropogenic aerosol emissions in Europe have been decreasing since the 1980s
 167 (Streets et al., 2006), and are projected to decrease further in the coming decades, re-
 168 sulting in a large reduction in aerosol concentrations over Europe, in particular scatter-
 169 ing sulfate particles (Gutiérrez et al., 2020). AOD is consequently largely reduced over
 170 Europe in 2021-2050 compared to 1971-2000 (Figure 1), with values ranging from -0.10
 171 to -0.33 on average over Central Europe (CEU, as defined in Seneviratne et al., 2012,
 172 shown in Figure 1), and from -0.05 to -0.14 over the Mediterranean (MED). The three-
 173 fold difference between the various simulations (Figure S1) is similar to the uncertainty
 174 found in the whole CMIP5 ensemble: Cherif et al. (2020) showed a decrease in MED AOD

Table 1. Characteristics of GCM-RCM pairs used in this study.

Institute	RCM	Grid	Driving GCM	Aerosols
AUTH	WRF ^a	50 km	CCSM4 (r6i1p1)	From GCM ^g
CNRM	ALADIN63 ^b	12.5 km	CNRM-CM5 (r1i1p1)	From GCM ^h
CNRM	ALADIN63 ^b	12.5 km	HadGEM2-ES (r1i1p1)	From GCM ^g
CNRM	ALADIN63 ^b	12.5 km	NorESM1-M (r1i1p1)	From GCM ^g
CNRM	ALADIN63 ^b	12.5 km	MPI-ESM-LR (r1i1p1)	From GCM ⁱ
ETH	COSMO-crCLIM ^c	12 km	MPI-ESM-LR (r1i1p1)	Clim ^j +trend ⁱ
GERICS	REMO2015 ^d	12 km	EC-Earth (r12i1p1)	Clim ^k +trend ^h
KNMI	RACMO22E ^e	12 km	EC-Earth (r3i1p1)	From GCM ^g
LAERO	RegCM ^f	50 km	EC-Earth (r12i1p1)	Clim ⁱ +trend ⁱ

RCM references: ^aPavlidis et al. (2020), ^bNabat et al. (2020), ^cLeutwyler et al. (2017),
^dJacob et al. (2012), ^evan Meijgaard et al. (2012), ^fGiorgi et al. (2012)
Aerosol references: ^gLamarque et al. (2011), ^hSzopa et al. (2013), ⁱKinne (2019)
^jKinne et al. (2006), ^kTanré et al. (1984)

175 ranging from -0.03 to -0.14 between the 1980-1999 and 2020-2039 periods. Therefore, our
176 ensemble well represents the range of possible futures in terms of anthropogenic aerosols.

177 In this section we will present and discuss the impact of this evolution of aerosols
178 on the relevant climate variables (shortwave (SW) radiation, near-surface temperature,
179 precipitation, evapotranspiration and cloud cover) in terms of future summer (June-July-
180 August, JJA) changes (2021-2050 minus 1971-2000).

181 3.1 Radiative budget

182 At the top of the atmosphere (TOA), the decrease of the concentrations of scat-
183 tering particles leads to a decrease of all-sky outgoing SW radiation in GCMs and RCMevol
184 simulations (Figure 1), respectively -7.7 Wm^{-2} and -5.2 Wm^{-2} in the multi-model av-
185 erage in CEU. This decrease is highest in RCMs with the highest decrease in AOD: ALADIN-
186 CNRM-CM5, ALADIN-NorESM1-M and ALADIN-HadGEM2-ES (Figures 2 and S2).
187 On the contrary, in RCMcst, TOA SW radiation is not substantially reduced (-1.2 Wm^{-2}
188 on average).

189 In parallel, the surface SW incoming radiation is distinctly increased over Europe
190 in GCMs and RCMevol simulations (Figure 1), respectively 11.3 and 10.9 Wm^{-2} in CEU,
191 while slightly decreased in RCMcst (-1.8 Wm^{-2}). In other words, regional models that
192 do not include evolving aerosols would be mistaken in the sign of the future evolution
193 of surface SW incoming radiation. In RCMevol, the future changes in both surface and
194 TOA SW radiation are spatially similar to the future changes in AOD.

195 Overall, the evolution of aerosols strongly impacts SW radiation. A significant lin-
196 ear relationship between SW radiation and AOD future changes has been found (Fig-
197 ure 2): $+6.3 \text{ Wm}^{-2}$ at the surface and -5.6 Wm^{-2} at TOA per -0.1 in AOD in CEU.
198 Similar relationships can be established for the MED domain (Figure S8): $+6.7 \text{ Wm}^{-2}$
199 at the surface and -6.3 Wm^{-2} at TOA per -0.1 in AOD.

200 3.2 Near-surface temperature

201 As for SW radiation, Figure 1 shows large differences in continental near-surface
202 temperature future summer changes between GCMs and RCMs. Over Europe, the warm-
203 ing between 1971-2000 and 2021-2050 is higher in GCMs ($+2.0^\circ\text{C}$ in CEU) than in RCM-
204 cst ($+1.4^\circ\text{C}$). Nonetheless, RCMs with evolving aerosols (RCMevol) have a stronger warm-
205 ing in Europe ($+1.7^\circ\text{C}$) than RCMcst, consistently with surface SW radiation variations.

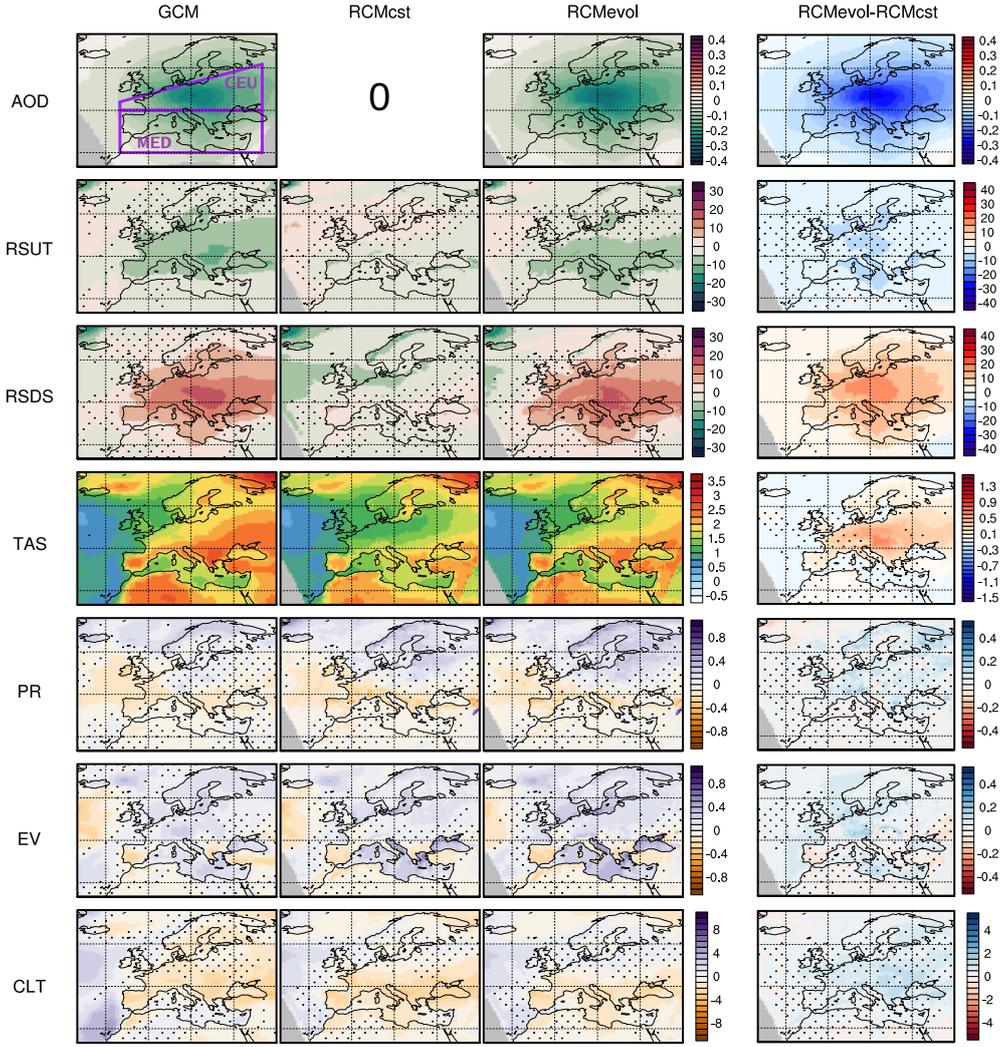


Figure 1. Multi-model averaged future changes (JJA, 2021-2050 minus 1971-2000) for the GCM, RCMcst and RCMevol ensembles. The last column gives the difference between RCMevol and RCMcst. Averages are presented for aerosol optical depth (AOD), TOA outgoing SW radiation (RSUT, Wm^{-2}), surface downwelling SW radiation (RSDS, Wm^{-2}), near-surface temperature (TAS, $^{\circ}C$), precipitation (PR, mm/day), evapotranspiration (EV, mm/day) and cloud fraction (CLT, %). The CEU and MED regions are shown in the top left-hand map. By construction, AOD future change for RCMcst is equal to zero. Black dots indicate areas where more than 20% of models disagree about the sign of the change.

206 The differences are maximal over Central Europe, as for AOD. Therefore, aerosols explain a significant part of the simulated warming over this period in Europe, on all RCMs
 207 explain a significant part of the simulated warming over this period in Europe, on all RCMs
 208 19% on average (up to 34% in ALADIN-NorESM1-M). Figure 2 also shows a significant
 209 relationship ($R^2 = 0.55$) between near-surface temperature and AOD future summer
 210 changes: $+0.3^{\circ}C$ in near-surface temperature per -0.1 in AOD in CEU. Given the un-
 211 avoidable decline of anthropogenic aerosols in Europe, these results imply that not con-
 212 sidering changes in aerosols would lead to underestimate warming in this region.

213 However, there are contrasts between the different RCMs regarding the aerosol effects on temperature. On the one hand, the models with a high aerosol trend are also
 214

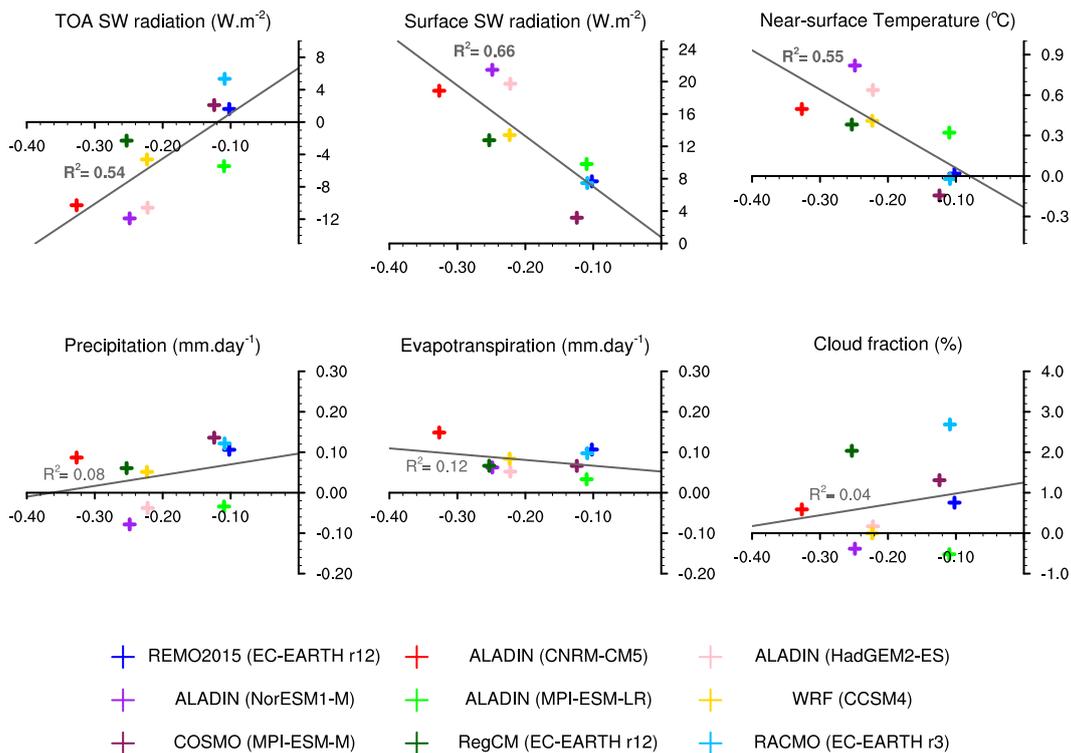


Figure 2. Averaged aerosol impact (RCMevol - RCMcst) on different parameters (TOA outgoing and surface downwelling SW radiation, near-surface temperature, precipitation, evapotranspiration and cloud fraction, y-axis for each plot) against AOD (x-axis). Averages are calculated for JJA, 2021-2050 minus 1971-2000, over the CEU domain. The black lines show the linear regression between the aerosol impact on the different parameters and AOD. Significant values of the square of the correlation coefficient (R^2) at level 0.05 are in bold characters.

215 those which have a larger warming (up to 0.8°C on average in CEU, reaching locally more
 216 than 1°C, Figure S4). On the other hand, three RCMs (REMO2015, RACMO and COSMO)
 217 show very little difference with and without evolving aerosols. The aerosol vertical dis-
 218 tribution, which is not identical in each RCM (Figure S10), could contribute to these con-
 219 trasts. For example, aerosols are maintained at lower altitudes in COSMO than in the
 220 other RCMs. Moreover, the evolution of near-surface temperature may be influenced by
 221 many other factors such as evapotranspiration response, cloud feedbacks.

222 In addition, no difference is seen over the ocean given that sea surface temperatures
 223 in RCMs are prescribed from their driving GCM. Therefore, the potential effect of aerosols
 224 on sea surface temperature (Nabat et al., 2015a) and associated feedbacks (slow adjust-
 225 ment, Liu et al., 2018) could not be studied here.

226 3.3 Water cycle

227 The additional surface heating due to aerosol changes could modify the climate pro-
 228 jections of regional water cycle. GCMs show here a drying of the Mediterranean basin
 229 for the period 2021-2050 (Figure 1), with a decrease of summer precipitation in South-
 230 ern Europe (extending to France and British Isles), and an increase of evapotranspira-
 231 tion over the Mediterranean Sea (extending to Central and Northern Europe), accom-
 232 panied by a decrease of cloud cover all over Europe. This pattern is also present in the
 233 multi-model average of both RCMcst and RCMevol but with some differences. Indeed

234 evapotranspiration increases more in RCMevol in CEU (0.15 mm/day in multi-model
 235 average against 0.07mm/day in RCMcst), likely due to the increase of incoming SW ra-
 236 diation at the surface. Even if there is no statistically significant relationship between
 237 the changes in AOD and evapotranspiration, this additional increase in evapotranspi-
 238 ration in CEU is noted in all RCMs (Figures 2 and S6), implying that the aerosol evo-
 239 lution might contribute to the drying of this region.

240 With regards to clouds, cloud fraction decreases less in RCMevol (-0.5 %) than in
 241 RCMcst (-1.2 %). In contrast, precipitation future summer changes are quite similar
 242 in RCMevol and RCMcst multi-model averages. However, these multi-model averages
 243 hide some discrepancies between the different RCMs (Figures S5 and S7). Indeed, the
 244 sign of the change of precipitation and cloud fraction between simulations with and with-
 245 out aerosols is not the same in all RCMs (Figure 2). Like evapotranspiration, no signif-
 246 icant relationship between AOD changes and precipitation/cloud cover changes can be
 247 established in CEU. Since the RCMs used here do not consider any aerosol effect on cloud
 248 microphysics (other than the cloud-albedo effect in the ALADIN63 radiative code), these
 249 changes in cloud cover and precipitation must come from semi-direct aerosol effects, namely
 250 changes in atmospheric dynamics or temperature profiles due to the absorption of so-
 251 lar radiation by aerosols.

252 **4 Discussion: The role of anthropogenic aerosols on GCM-RCM in-** 253 **consistencies**

254 Given the strong impact of anthropogenic aerosols on climate change simulated by
 255 RCMs, the question is whether this will reduce inconsistencies with global simulations.
 256 Figure 3a presents the averaged future summer changes of each RCM against the changes
 257 in the driving GCM.

258 Both for TOA and surface SW radiation, RCM simulations with evolving aerosols
 259 are irrefutably much closer to their driving GCM than to the respective RCM simula-
 260 tions with constant aerosols. Results are more subtle for near-surface temperature. A
 261 better GCM-RCM consistency is noted for six GCM-RCM pairs (the four ALADIN63
 262 simulations, WRF and RegCM), but little impact from the evolution of aerosols is found
 263 for COSMO, REMO2015 and RACMO. These discrepancies in near-surface tempera-
 264 ture could be explained by changes in water cycle (Boé et al., 2020). All models show
 265 an increase of evapotranspiration in their simulations with evolving aerosols compared
 266 to their simulations with constant aerosols, which does not always go along with a bet-
 267 ter GCM-RCM consistency. It is probably due largely to the increased SW radiation.
 268 Nor do changes in precipitation and cloud cover systematically improve GCM/RCM con-
 269 sistency. The GCM-RCM inconsistencies in evapotranspiration could also be explained
 270 by other processes independently of aerosols such as the impact of the physiological ef-
 271 fect of CO₂ on changes in evapotranspiration (Boé et al., 2020), not considered in RCMs.

272 All these changes between RCMcst and RCMevol and their consequences on GCM-
 273 RCM consistency are summarized in Figure 3b, represented as polygons, joining the multi-
 274 model future summer changes for each variable in CEU, respectively for GCMs, RCM-
 275 cst and RCMevol. Aerosols are thus shown to improve GCM-RCM consistency for near-
 276 surface temperature, TOA and surface SW radiation. It is all the more important for
 277 surface SW radiation, as the sign of the change was different between GCMs and RCM-
 278 cst, while this parameter is increased in GCMs and RCMevol. Similar improvement has
 279 been found for radiation over the Mediterranean (Figure S9). With regards to near-surface
 280 temperature, the range of simulations showing the strongest warming in CEU (more than
 281 2°C between 2021-2050 and 1971-2000) is only covered by GCMs and RCMs with evol-
 282 ving aerosols (blue crosses in Figure 3b). No simulation with constant aerosol (green crosses
 283 in Figure 3b) significantly exceeds the 2°C warming value in CEU, and the average of
 284 RCMcst itself is out of the range of the different driving GCMs.

285 However, our results also suggest that for the three other variables (precipitation,
 286 cloud cover and evapotranspiration), aerosol radiative forcing trends are not directly linked

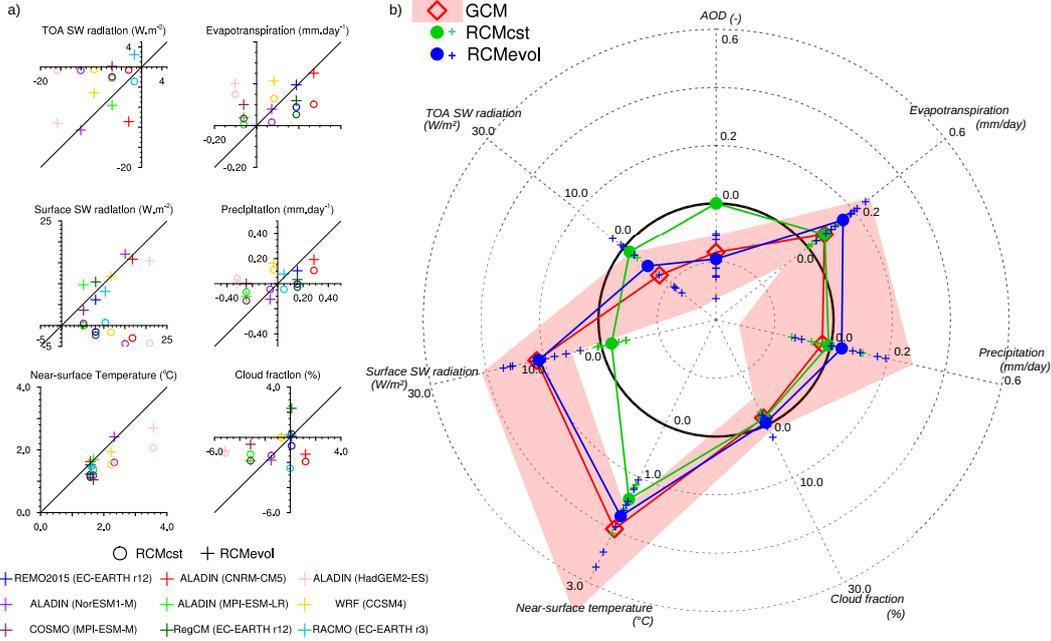


Figure 3. GCM/RCM consistency in climate change (JJA, 2021-2050 minus 1971-2000, CEU domain). a) Averaged changes in RCM simulations (y-axis) against their driving GCM simulation (x-axis), for the same parameters as in Figure 2. The black diagonal lines indicate the $y=x$ line. b) Multi-model averaged changes. A radius is assigned to each variable, for which the change is derived respectively for the multi-model averages of GCM (red square), RCMcst (green point) and RCMeval (blue point). Individual models for RCMcst and RCMeval are noted in green and blue crosses respectively, while the red shaded area shows the range of all GCM simulations (min/max). The bold black circle indicates no change, and each dotted circle is separated by $10 Wm^{-2}$ for TOA and surface SW radiation, $1.0^{\circ}C$ for near-surface temperature, $0.2 mm/day$ for evapotranspiration and precipitation, 0.2 for AOD and 10% for cloud fraction.

287 to GCM-RCM inconsistencies. Figure 3b confirms that the respective RCMeval and RCM-
 288 cst ensembles cannot be distinguished from the ensemble of their driving GCM for these
 289 three variables. This result must be qualified by the fact that aerosol-cloud interactions
 290 are poorly represented in the simulations used here. These microphysical processes are
 291 complex, depending both on aerosol and cloud properties, and need to be better under-
 292 stood and then properly integrated into models to assess their impact on climate (Seinfeld
 293 et al., 2016).

294 These results highlight the fact that GCM-RCM conflicting signals need to be docu-
 295 mented, understood and solved to improve the robustness of future regional climate in-
 296 formation. Disentangling the origin of the conflict is possible although not always easy.
 297 The spatio-temporal variability of aerosol radiative forcing is one of the drivers of cli-
 298 mate change, and needs therefore to be better considered in upcoming regional climate
 299 simulations, notably in the next generation of CORDEX runs driven by CMIP6 GCMs.
 300 Besides Europe, the role of the regional aerosol forcing could be relevant for other ar-
 301 eas, such as China, India, North America, or South Africa.

5 Conclusions

The present study uses a diversified multi-model ensemble of GCM-RCM simulations to disentangle the role of aerosols in climate change over Europe, and their possible contribution to GCM-RCM inconsistencies. Regional future simulations (2021-2050) with and without the evolution of anthropogenic aerosols, with respect to equivalent historical simulations (1971-2000), are compared and analysed. Results show that aerosols play an essential role in the future evolution of SW radiation, insofar as the decrease of their concentrations due to reduced anthropogenic emissions is responsible for an increase of surface incoming SW radiation and an associated decrease of outgoing SW radiation at TOA. This change in aerosols also induces an extra surface warming in Europe in most of the simulations presented here. The future summer changes in both SW radiation and near-surface temperature have a significant response to anthropogenic aerosol changes. However, no clear response to the evolution of aerosols has been found for cloud cover and precipitation future changes, even if all models show a slight increase of evapotranspiration.

Besides, this study provides some answers to the question of GCM/RCM inconsistencies. Time-varying anthropogenic aerosols have been shown to increase GCM/RCM consistency in SW radiation (both for the surface and TOA) and, to a lesser extent, near-surface temperature, but not for water cycle (precipitation, evapotranspiration, cloud cover). These results motivate an improved representation of aerosols in the next generation of CORDEX for past and future runs, as well as a closer collaboration between GCM and RCM developers and users. It is indeed important to motivate climate modelling communities to more systematically look for GCM-RCM conflicting messages in order to document them, to try to understand their origin and even better to solve the conflict either by correcting the source of the inconsistency or by deciding what is the most reliable information source. It is also worth mentioning that although aerosols play an important role in climate change, the future evolution of aerosols itself remains highly uncertain, whatever the scenario and the type of modelling (RCMs, GCMs).

Open Research Section

The CMIP5 and CORDEX simulations used in this study are available on the Earth System Grid Federation portal (<https://esgf-node.ipsl.upmc.fr/projects/esgf-ipsl/>). The dedicated FPS-Aerosol simulations for the nine GCM-RCM pairs (Nabat et al., 2024) are available at <https://doi.org/10.5281/zenodo.13736588>.

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